Reduce the Transverse Distortion of Butt Welded Plates Using Genetic Algorithm

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Abstract

This paper presents a study on optimization of process parameters using genetic algorithm to reduce the transverse distortion in 304 L stainless steel butt welded plates. Distortion, the major problem in welded plates, results from the expansion and contraction of the weld metal and adjacent base metal during the heating and cooling cycle of the welding process. During this heating and cooling cycle, many factors affect shrinkage of the metal and lead to distortion, such as physical and mechanical properties that change as heat is applied. The geometry parameters of weld section and the environmental factors are important in distortion. In this paper, the effects of V shape angles and thickness of plates are investigated on the transverse distortion under temperature dependent of thermal coefficient condition. For this purpose, the finite element based software ANSYS, has been employed to evaluate the transverse distortion. Finally, to reduce the transverse distortion in 304L stainless steel butt welded plates, MATLAB software has been used. The results obtained from the finite element analysis in different models are helpful to produce the collection of data which are optimized using the genetic algorithm. Finite element results show that by increasing plate thickness, the transverse distortion has increased and by increasing V shape angle, this kind of distortion increased. Also, results show that the optimization process has been successfully developed.

Keywords

Arc Welding; 304L Stainless Steel; Distortion; Finite Element; Genetic Algorithm

Introduction

Arc welding is a type of welding that uses a welding power supply to create an electric arc between an electrode and the base material to melt the metals at the welding point. Because of the versatility of the process and the simplicity of its equipment and operation, shielded metal arc welding, one of the world's most popular welding processes, dominates other welding processes in the maintenance and repair industry, and continues to be used extensively in the construction of steel structures and in industrial fabrication. Arc welding process is suitable for joining thin and medium thick metals such as stainless steel plates. One of the important issues in welded structures is the exit of residuals stress and distortion resulted by welding. Welding involves highly localized heating of the metal being joined together. The temperature distribution in the weldment is therefore nonuniform. Normally, the weld metal and the heat affected zone (HAZ) are at temperatures substantially above that of the unaffected base metal. Upon cooling, the weld pool solidifies and shrinks, exerting stresses on the surrounding weld metal and HAZ. If the stresses produced from thermal expansion and contraction exceed the yield strength of the parent metal, localized plastic deformation of the metal occurs. Plastic deformation results in lasting change in the component dimensions and distorts the structure. This causes distortion of weldments. Distortion is a common problem experienced in the welding fabrication of thin plate structures. There are many factors that can cause welding or cutting distortion. Some of the factors that should be considered include the degree of restraint; the thermal and other properties of the parent material; inherent stresses induced from previous metal-working processes such as rolling; forming and bending; design of weldment; accuracy of manufacture and the nature of the welding process itself – the type of process; symmetry of the joint; preheat and the number and sequence of welds required. Study on the distortion in the weld spot is necessary in order to increase the life of these joints. Because distortion measurement needs laboratory equipments, facilities, much time and high costs; study and numerical analysis of these cases are important due to the high efficiency of these numerical methods. Several optimization techniques have been applied to optimize welding process parameters. Genetic alghorithm is widely used as the optimization method in evolutionary computation. By developing the computer techniques, statistical methods and finites elements analysis have been used to collected deta for optimization with genetic alghorithm. For example, Arnold et al (1989) used PAFEC software in order to

estimate residual stress in multi-pass fillet weld. Tahami and Sorkhabi (2009) have also studied the effect of the welding-electrode speed using birth and death of finite elements. They have shown that use of the 3D and transient model will lead to more accurate and realistic results which are well compared with the test data. Accurate and reliable residual stress prediction and measurements are essential for structural integrity assessment of components containing residual stresses. Tahami and sorkhbi (2009) have examined the thicknesses effect on the residual stress states in butt-welded 2.25Cr1Mo steel plates. Finite element analyses results show that by increasing the plate thickness, the residual stresses increase and the residual stress affected zone becomes larger. Huajun Zhang et al (2008) have studied the process controlling of angular distortion in asymmetrical double sided arc welding (ADSAW). Mollicone et al (2006) have studied numerical simulation welding based on finite element methods, therefore, offering a comprehensive solution for the prediction of residual stress and strain as well as welding distortion in welded structures. Correia et al (2004) have explored the possibility of using GA as a method to determine optimal settings of a GMAW process. The best values of three control variables have been chosen. They have concluded that GA is able to locate near optimum conditions. Saurav Datta et al (2010) have done multi objective optimization of submerged arc welding process using particle swarm optimization and have applied response surface methodology to develop mathematical models for depth of penetration, reinforcement and bead width. Farhad Kolahan et al (2010) have been studied an approach to predict and optimize weld bead geometry in arc welding. Kim et al (2003) have optimized the quality of arc-metal welding with protective gas and found that penetration and total area increased when the welding current is increased and decreased when travel speed is increased. In current paper, distortion considering the least limits and changing the physical and mechanical qualities with temperature in single-pass butt-welding of two 304L stainless steel plates has been analyzed by using the finite element method and it has been finally optimized by genetic algorithm. Finite element based software ANSYS with an uncoupled thermo mechanical solution analyses has been used. A two dimensional model in three different thicknesses and angle of plates has been developed to calculate the temperature fields and the welding distortion. In the optimization procedure, the distortion has been taken as objective function with the limits of the process parameters as constraints. The optimization of process parameters has been done using genetic algorithms (GA). MATLAB software has been used in order to model the genetic algorithm.

Distortion

Distortion or deformation can occur during welding as a result of the non-uniform expansion and contraction of the weld and base metal during the heating and cooling cycle. Stresses form in the weld as a result of the changes in volume, particularly if the weld is restrained by the fixed components or other materials surrounding it. If the restraints are partly removed, these stresses can cause the base material to distort and may even result in tears or fractures. Of course, distortion can be very costly to correct, so prevention is important. Since the temperatures are the highest in the region near the welding torch, this region expands more than regions further away. During the heating, the stresses in the region near the weld are compressive plastically because the thermal expansion in this region is restrained by surrounding metal with lower temperature and higher yield stress. When the welding has been completed and the plate starts to cool, it deforms in the opposite direction. If the material has been completely elastic during the entire period of the heating and cooling cycle, the plate would return to its initial shape with no residual distortion. However, for metals like steel and aluminium plastic deformations occur. As a result of the compressive plastic strains produced in the regions near the welding zone, the plate continues to deform after passing its initial shape, which results in a negative final distortion when the plate cools down to its initial temperature, as illustrated in Fig. 1. The deformations may be so large that the object cannot fulfill its intended function or fit its intended location.
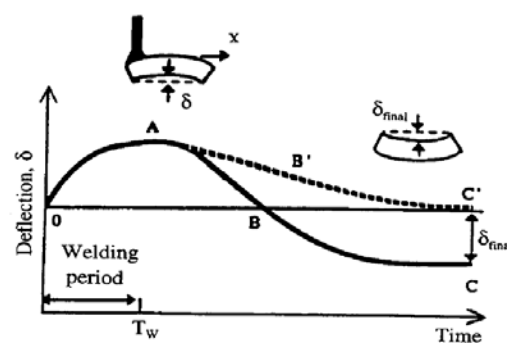

FIG. 1 DEFORMATION OF A STEEL PLATE DURING AND AFTER WELDING.

There are various types of distortion and dimensional change including longitudinal; transverse; angular;

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twisting and bowing. Two or more types of distortion may occur at the same time. The effects of weld shrinkage can never be entirely eliminated but can be kept at minimum. When cutting, it is possible to limit distortion by supporting the plate so it can expand freely without buckling; ensuring that the plate is flat; allowing sufficient weld material from corners and using a jig-saw pattern to lock the cut pieces together when multiple cutting. Distortion can be avoided or significantly reduced when structural steelwork was welded by using fixing devices, such as strong backs or wedges to pre-set seams in plates; flexible clamps to bring parts to the required gap before welding or clamps for thin sheet welding. Longitudinal stiffeners can also be used to limit this type of bowing. It is also important to use the correct welding sequence, such as welding the frame before a cover plate. Pre-bending or pre-setting techniques may also help to prevent distortion and water can be used to cool the process. In summary, if welding distortion is likely to be a problem, it can be avoided or minimized by advance planning and following best practice. In this paper, transverse distortion in arc welding process has been studied.

Finite Element Analyses of Welding Process

The evolution of the temperature fields and distortion has been investigated by means of thermal elastic plastic finite element method. In order to accurately capture the distortion in the welded plate, a two-dimensional finite element model is developed. Finite element software provides two methods to simulate the welding process. Two frequently used methods are titled as coupled and uncoupled formulation. The coupled formulation is basically used in the bidirectional coupled applications, in which the result of thermal analysis affects the structural analysis. By the direct method, the element selected in the simulation should consist of both thermal and structural degrees of freedom. The thermal and structural results can be obtained in the same time after the calculation. However, in some cases, the effect of the thermal analysis on the structural result is much insignificant and can be even neglected. In this method, the thermal and structural analyses are performed separately. The solution procedure includes two steps. First, the temperature distribution and its history in the welding process is computed by the heat conduction analysis. Then the temperature history is employed as a thermal load in the subsequent mechanical elastic–plastic calculation of the structural field. The quality of distortion resulting

from welding depended on residual stress and thermal and structural fields, so the thermo-mechanical behavior of the weldment during welding is simulated using uncoupled formulation, because the dimensional changes in welding are negligible and mechanical work done is insignificant compared to the thermal energy from the welding arc. Thermal transmit in welding is an issue dependent on time. In order to model the entrance thermal, a specific amount of weld spot is put in certain temperature to affect the acceptable volume of influenced place. In this paper the equation suggested by Argris (Deng et al 2006) has been used in order to apply the border thermal conditions which is a combination of replacing convection of all surface with environment, radiation and conduction heat transfers. The radiation and the convection are important at high and lower temperature, respectively, at distances away from the arc. The boundary conditions are assumed as combinations of convection and radiation. In this equation, the coefficient of combined thermal transmit is expressed as the following:

$$H = \begin{cases} 0.0668T(W/m^2)\, 0 < T < 500^0 C \\ 0.231T - 82.1(W/m^2)T > 500^0 C \end{cases} \quad (1)$$

In mechanical analysis, the thermal history obtained by thermal analysis is applied to structure, then residual stress and distortion in each period are evaluated by a elastic-plastic analysis. This operation continues until change of piece thermal to environmental temperature.
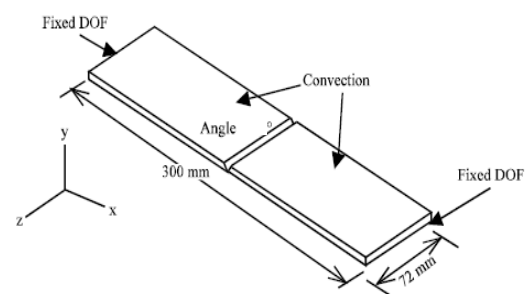
Model and Material

FIG. 2 JOINT CONFIGURATION AND FE BOUNDARY CONDITIONS FOR TWO SEMI-INFINITE 304L STAINLESS STEEL LOW ALLOY-FERRITIC STEEL PLATES

TABLE. 1 CHIMICAL COMPOSITION OF 304L SS IN PRECENT

C	Si	Mn	P	S	Cr	Mo	Ni	Cu	N	V
0.019	0.41	1.75	0.036	0.006	18.28	0.34	8.04	-	0.04	-

Two semi-infinite 304 L stainless steel low-alloy-ferrite steel plates with 150×72 mm^2 with different thickness and angles; as shown in Fig. 2 have been modeled. In

this steel, the maximum amount of carbon is 0.03. The caused decrease of corrosion rate has been compared to 304 L stainless steel. It is the most versatile and widely used stainless steel, available in a wider range of products with superior forming and welding characteristics. Also, the chemical composition of the metal is given in Table. 1.

Material or material-related characteristics have been depicted that influence the development of welding distortion include thermal conductivity, heat capacity, thermal expansion coefficient, elastic modulus and Poisson's ratio, yield strength, work hardening coefficient, thermodynamics and kinetics of phase transformations, mechanisms of transformations, and transformation plasticity. To accurately predict welding distortion, the thermal and mechanical characteristics should be considered. The material's thermal and mechanical properties are shown in Fig. 3 and Fig. 4 which vary with temperature.
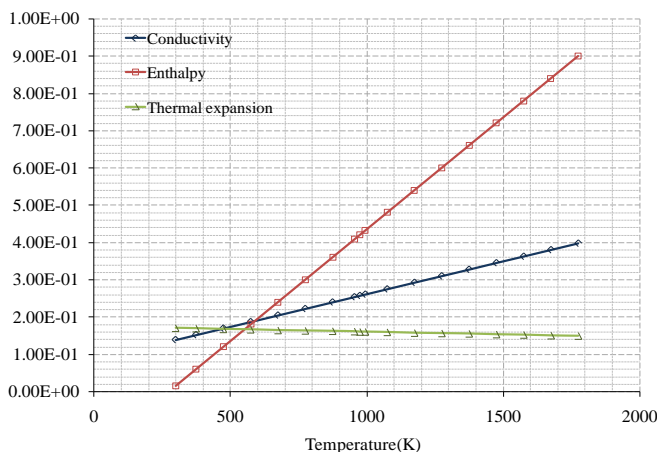
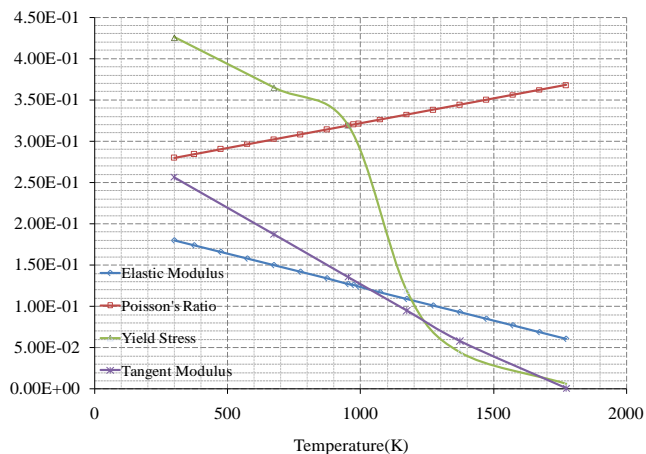FIG. 3 TEMPERATURE-DEPENDENT THERMAL PHYSICAL PROPERTIES

FIG. 4 TEMPERATURE-DEPENDENT THERMAL MECHANICAL PROPERTIES

In this paper, in order to study the angle and thickness effect on distortion, the plate with thicknesses of 2,3

and 4 mm; weld-groove angles of 30^0, 45^0, 60^0 has been taken into consideration and due to the symmetry, only half of the weld and plates have been modeled. Evaluating the three-dimensional distortion requires a considerable amount of computational time and cost. Herein, a two-dimensional axisymmetric model has been designed to calculate the distortion. The type of filling metal is considered as similar to base metal so are the thermal and mechanical properties of weld metal. The temperature of the melted filler material is set to be 1773 Kelvin. Since the plate can dissipate heat through convection. For thermal analysis, eight-nodes, two-dimensional brick thermal element plane 77 is used. For the mechanical analysis, the element is converted to the corresponding structural element. By means of inputting commands to change thermal element type to structural type, the element plane 77 can be automatically replaced by the equivalent structural element plane 183 which is also an eight-nodes, two-dimensional element but has plasticity, hyper-elasticity, stress stiffening, creep, large deflection, and large strain capabilities. In this research, the element mesh that plays an essential role in the calculation remains the same as the thermal analysis geometric model. Fig. 5 shows the FE mesh of the weld and the plate.
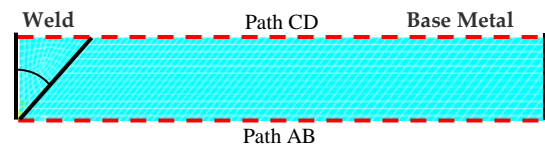
FIG. 5 THE FE MESH OF THE WELD AND THE PLATE, TWO PATHS DEFINEED WELDED PLATE TO PRESENT RESULTS

Theoretical Considerations

Welding distortion distribution is calculated by finite element techniques. Theoretical considerations can be assessed either by a thermal or a mechanical model.

Thermal Analysis

The following equations were used in the thermal model analyses:

$$-\left(\frac{\partial R_x}{\partial x} + \frac{\partial R_y}{\partial y} + \frac{\partial R_z}{\partial z}\right) + Q(x, y, z, t) = \rho C \frac{\partial T(x, y, z, t)}{\partial t} \quad (2)$$

Where R_x, R_y, R_z are the rates of heat flow per unit area, $T(x, y, z, t)$ is the current temperature, $Q(x, y, z, t)$ is the rate of internal heat generation, ρ is the density, C is the specific heat and t is the time. The model can then be completed by introducing the Fourier heat flow as:

$$R_x = -k_x \frac{\partial T}{\partial x} \quad (2a)$$

$$R_y = -k_y \frac{\partial T}{\partial y} \qquad (2b)$$

$$R_z = -k_z \frac{\partial T}{\partial z} \qquad (2c)$$

Where k_x, k_y, k_z are the thermal conductivities in the x, y and z directions respectively. The thermal conductivity and specific heat, K_x, K_y, K_z, ρ, C are considered temperature dependent and therefore, the materials are regarded as having nonlinear behavior. By considering the process in the material non-linear, the parameters k_x, k_y, k_z, ρ , C are a function of temperature. Inserting equations (2a), (2b), (2c) into equation (2), yields. The differential equations governing heat conduction in a solid body can be written as:

$$\frac{\partial}{\partial x}(k_x \frac{\partial T}{\partial x}) + \frac{\partial}{\partial y}(k_y \frac{\partial T}{\partial y}) + \frac{\partial}{\partial z}(k_z \frac{\partial T}{\partial z}) + Q = \rho C \frac{\partial T}{\partial t} \qquad (3)$$

Equation (3) is the differential equation governing heat conduction in a solid body. The general solution is obtained by accepting the initial and boundary conditions: initial condition

$$T(x, y, z, 0) = T_0(x, y, z) \qquad (4)$$

$$(k_x \frac{\partial T}{\partial x} N_x + k_y \frac{\partial T}{\partial y} N_y + k_z \frac{\partial T}{\partial z} N_z)$$
$$+ q_s + h_c(T - T_\infty) + h_r(T - T_r) = 0 \qquad (5)$$

Where N_x, N_y, N_z are the direction cosines of the outward drawn normal to the boundary, h_c is the convection heat transfer coefficient, h_r is the radiation heat transfer coefficient, q_s is the boundary heat flux, T_∞ is the surrounding temperature and T_r is the temperature of the radiation heat source. The radiation heat transfer coefficient is expressed as:

$$h_r = \sigma \varepsilon F(T^2 + T_r^2)(T + T_r) \qquad (6)$$

In which α is the Stefan–Boltzmann constant, ε is the effective emissivity and F is a configuration factor.

Mechanical Analysis

Two basic sets of equations related to the mechanical model, the equilibrium equations and the constitutive equations, are considered as follows.

(a) Equations of equilibrium

$$\sigma_{ij.j} + \rho b_i = 0 \qquad (7a)$$

and

$$\sigma_{ij} = \sigma_{ji} \qquad (7b)$$

Where σ_{ij} is the stress tensor and b_i is the body force.

(b) Constitutive equations for a thermal elasto-plastic material. The thermal elasto-plastic material model,

based on the von Mises yield criterion and the isotropic strain hardening rule, is considered. Stress–strain relations can be written as:

$$[d\sigma] = [D^{ep}][d\varepsilon] - [C^{th}]dT \qquad (8a)$$

and

$$[D^{ep}] = [D^e] + [D^p] \qquad (8b)$$

Where $[D^e]$ is the elastic stiffness matrix, $[D^p]$ is the plastic stiffness matrix, $[C^{th}]$ is the thermal stiffness matrix, d_ε is the stress increment, d_σ is the strain increment and dT is the temperature increment.

Optimization of Angular Distortion

The purpose of optimization is to minimize distortion and to find the optimum process parameters for minimum distortion. Genetic algorithm, used for optimization, is an adaptive search and optimization algorithm that mimics principles of natural genetics. Due to their simplicity, ease of operation, and global perspective, have been successfully used in a wide variety of problem domains.

Genetic Algorithm

Among the optimizing methods inspired by the nature, genetic algorithms considered as the most developed ones and based on natural development principle has been used as a powerful tool for optimization. The data processed by GA includes a set of chromosomes with an infinite length in which each bit is called an gene in biology system.

Each chromosome determines a point in searching space of the issue and is made of some 0 and 1. A selected number of strings are called population. The GA is a repeating process in which each population at a given time is known as generation. Generations of the initial population of strings are determined randomly. Thereafter the compatibility value of each member is computed. In order to direct searching operation toward the optimum point in a process which is dependent on natural choice, the new generation is produced based on the propriety of existing population. The population is then operated by the three main operators, reproduction, crossover and mutation to create a new population which is then evaluated and tested for determination. The current population is checked for acceptability or solution. The iteration is stopped after the completion of maximum number of generations or on the attainment of the best results.

Implementation of GA

In this paper, the target function is displacement that

results from welding parallel to weld. This function is represented mathematically by regression analysis. After the regression coefficients have gained, a function is obtained that is indicative of relations between thickness, angle and displacement. The related operation has been done in MATLAB software. Among the existing data, this software is fitted with a series of points and finally displayed as a plate in a three dimensions space shown in Fig. 6. It should be noted that due to the use of regression, when there is unrelated data, the diagram isn't fitted on it. When real models are used in optimizing process, it should be ensured that results obtained by the algorithm are valid. This means that variables should be limited within the real constraints to prevent unreal results production. This has been done by the evaluation of simulation error (R_2). As far as this rate is close to 1, the accuracy of the modeling is high. For this model R_2=0.9803. To optimize, the MATLAB Genetic Algorithm Toolbox has been used. Target function is to make minimize the displacement. Two parameters, thickness and angle, have been considered as the input data. These parameters and their ranges are obtained by the analysis done in ANSYS software.
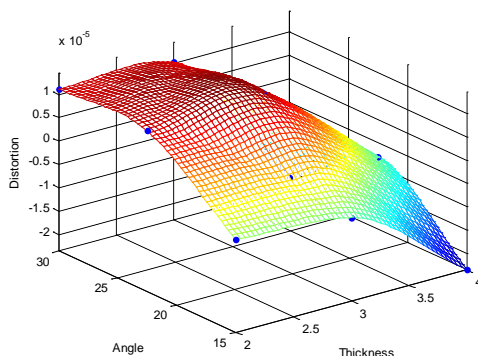

FIG. 6 SURFACE FOR INTERACTION EFFECT OF ANGLE AND PLATE THICKNESS ON DISTORTION

Results and Discussion

The large progress in development of reducing the residual stress and distortion in welding process has been observed during the last 10-15 years, but using the evolutionary optimization in this topic is still rather few. In this paper, the distortion in the Y-direction has been considered.

Since by changing the geometrical conditions including the change of V shape angle, thickness and also the environmental conditions such as the convection, the rate of residual stress and distortion are changed. The influence of process parameters such as displacement on the distortion was studied using

the developed model. The mathematical model developed can be used to predict distortion by substituting the values of the respective process parameters and by using the genetic algorithm method obtained optimum displacement.

Thermal analysis covers the time history and temperature gradient. Two nodes, "A" and "C" for the time history, and two path, "AB" and "CD" along the length of the plate, for temperature gradient and mechanical analysis have been determined as shown in Fig. 5.

Thermal Analysis Results

Welding process is done in the environmental temperature (298 Kelvin), and the welding time was 4 seconds. According to Fig. 7, the maximum temperature in t= 4 sec, is 1773 k which is the same of welding temperature. Because the temperature of piece is the same as environmental temperature, at this time diagram has more slopes to reach the environmental temperature. After 4 seconds, by stopping welding, temperature due to the thermal exchanging through free replacing with the surrounding air and also the thermal distribution in sheets through conductivity decreases. Weld temperature decreases by passing time and the temperature of another parts increases.
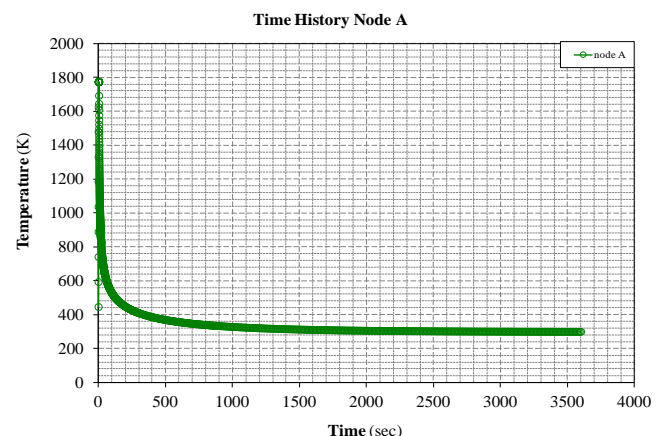

FIG. 7 TIME HISTORY OF NODE "A"

Fig. 8 shows the variation of the temperature distribution with time on the plate surface along path "AB". It can be seen that the maximum temperature reduces from 1773 K to 350 K in 600 seconds. In addition, this figure shows that the cooling down rate is high at the first 100 seconds, and then after 600 seconds it reaches an almost steady-state rate at 350 K. At the beginning, the temperature reduction in the area close to the weld axis shows the quenching effect; but along the path and in the area close to the plate

sides its temperature increases from 298 K to 350 K. The thermal analysis has indicated that after 3600 seconds the plate reaches the steady state temperature distribution. Therefore, the distortion at this stage has been presented here.
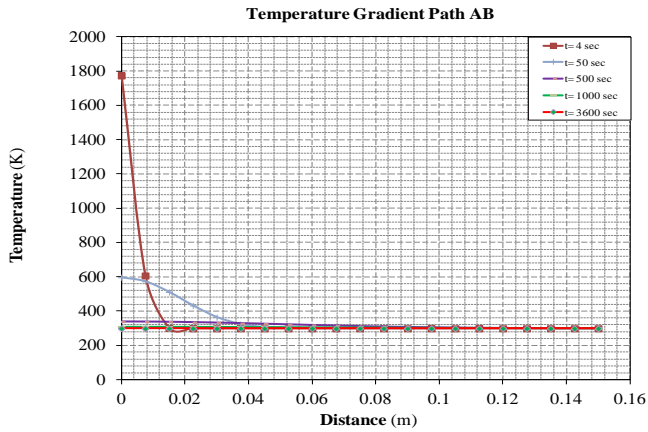

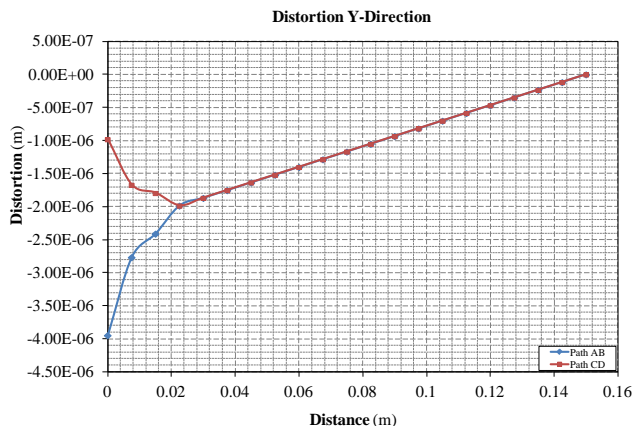FIG.8 GRADIENT OF TEMPERE ALONG PATH "AB"

Mechanical Analysis Results

FIG. 9 DISTRIBUTION OF THE DISTORTION ALONG PATH "AB" AND "CD"

To study the effect of the plate thickness and angle on the displacement of the plate, nine different cases have been calculated and only three results have been shown. The displacement curves with respect to distance of this paths in all cases are plotted in below Figures, showing the distortion pattern along the Y axis which is perpendicular to the welding line in which the deformations are plotted. The differences happen in the location close to the welding zone and the peak value in the plate edge, owing to the boundary condition configuration. According to Fig. 9, the largest displacement in the Y-direction and in the positive direction is about 30 mm of weld zone. The amount of displacement in the Y-direction is negative and in weld spot it increases about 30 mm in the bottom path "CD" and decreases in the upper path "AB". It has been observed that the final displacement

changes from more then 2 mm to about 5.5 mm when the thickness of the plate varies from 2 mm to 3 mm. After that, when the thickness further increases to 4 mm, the final displacement reduces to less than 2.5 mm. FIG. 9 plots the displacement curves along the the welding direction in one cases. Thicker plate results in more uniform deformed pattern.
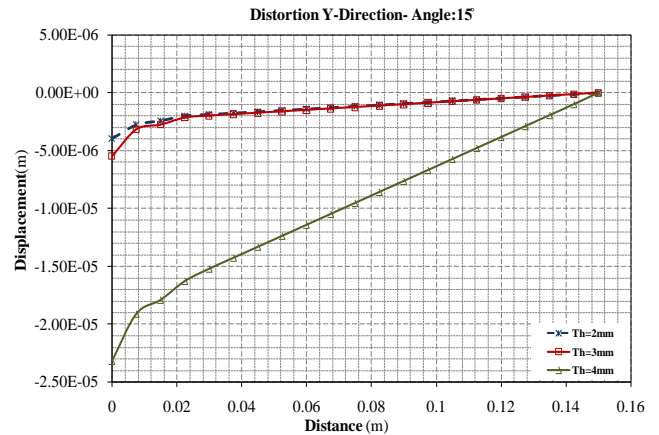

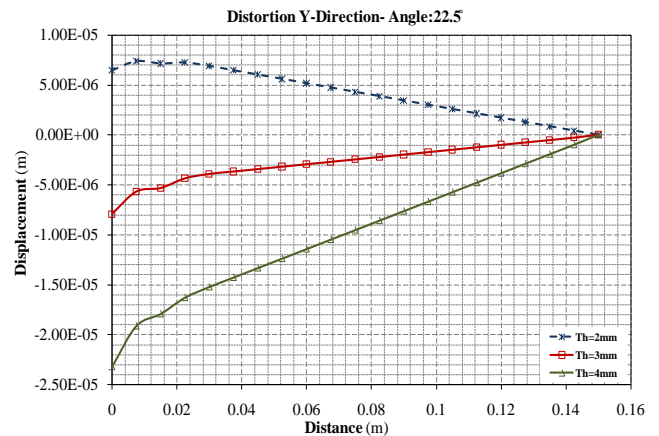FIG. 10 DISTRIBUTION of the DISTORTION ALONG PATH "AB"

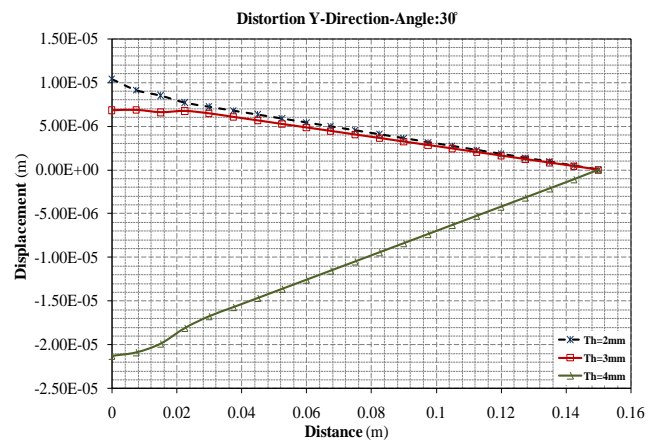FIG. 11 DISTRIBUTION OF THE DISTORTION ALONG PATH "AB"

FIG. 12 DISTRIBUTION OF THE DISTORTION ALONG PATH "AB"

As it can be seen in Fig. 10, Fig. 11 and Fig. 12 that

distortion changes in Y-direction along the path at different angles exhibit similar trend. By increasing the plate thickness, the distortion has been increased.

Conclusions

The following conclusions can be made from the investigation:

1. It can be said that weld spot and HAZ has the most significant distortion. Distortion amounts can be reduced by taking away the weld line.

2. Central composite designs can be conveniently used to predict the direct and interactive effects of different combinations of process parameters within the range of investigation.

3. The maximum amount of distortion is derived from the lateral distortion in welding zone so the distortion in the bottom path is more than upper one.

4. The optimization of process parameters has been done using GA and an algorithm was successfully developed using MATLAB to do the optimization

5. With GA based optimization used in this paper, it would be possible to minimize the distortion by using optimal process parameters.

6. According to the results of the genetic algorithm, the plate with the largest thickness and the least angle has the least distortion.

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